On Luminous Efficiency and the Mechanical Equivalent of Light.

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(Abstract.)

The determination of the efficiency of various forms of illuminants, and of the power expended in light production, does not appear to have received the attention it deserves in this country, nor have the labours of workers in Germany and in the United States as yet sufficed to permit of definite values being adopted for luminous efficiencies, or for the mechanical equivalent of light. In what follows, an account of some observations made by Mr. A. C. Jolley and the writer, with the object of determining the mechanical equivalent of light, will be given. For this purpose an attempt was first made to find the luminous efficiencies and total consumption of some of the newer highly incandescent electric lamps; and this was followed by a direct determination by a bolometer in the spectrum.

I. *Luminous Efficiency.*

Let Q be the total power consumption of a source.

R the "total radiation" $= \int_0^\infty I_\lambda d\lambda$, the remaining power, Q $-$ R being dissipated by conduction or convection.

L the "luminous radiation" $= \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda$, where λ_1 and λ_2 are the limits of the visible spectrum, say, $0{\cdot}39\,\mu$ and $0{\cdot}76\,\mu$, respectively.

L_λ the "equivalent luminous radiation" $= \int_0^\infty \kappa_\lambda I_\lambda d\lambda$, where κ_λ is a factor which is proportional to the luminosity and taken to be unity for a wave-length of $0{\cdot}54\,\mu$, which is that of maximum luminous utilisation of energy.

Then the "luminous efficiency" in its ordinary acceptation is $\eta = L/Q$. This is the quantity which is called by Nichols* the "total efficiency." Methods which take no account of conduction or convection losses seek to determine the ratio $\eta_R = L/R$, which Nichols terms the "radiant efficiency." Lastly, a suggestion of Dr. Guilleaume's† leads to a new definition, $\eta_\lambda = L_\lambda/Q$, which might be termed the "reduced luminous efficiency," as it is reduced in terms of the standard monochromatic light. It is obvious that while

* 'Phys. Rev.,' vol. 17, p. 267.

† 'Soc. Int. Elec.,' Bull. V, pp. 363–400.

with the ordinary definition a source would have unit efficiency if L = Q, or the whole of the energy were within the spectrum, and might yet be a very ineffective source as an illuminant if its radiation were confined to near the ends of the visible spectrum; Dr. Guilleaume's definition would only lead to unit efficiency in the case of a monochromatic source of wave-length $0{\cdot}54\,\mu$.

II. *Measurement of the Mechanical Equivalent of Light.*

The most direct mode of procedure is obviously to allow a beam of light of any required quality to fall simultaneously on some form of radiometer and a photometer; and to compare the indication of the radiometer with that obtained from a known source of radiation at a given distance. As nearly all devices for measuring low intensities of radiation are liable to troublesome variations, it is of the greatest importance that the comparison between the radiation in the beam under test, and the known radiation, should be effected as quickly and easily as possible, and with the minimum of disturbance.

Fig. 1 shows the arrangement of apparatus adopted after consideration of the above points. A small intense source of light such as an arc or Nernst filament was employed, in conjunction with a lens, L, and carbon bisulphide prism, P, to form an approximately pure spectrum at the photometer and radiometer box, B. By using a narrow slit an approximately monochromatic light of any required wave-length could be projected on to the photometer, while by widening the slit a band of any width up to the entire limits of the visible spectrum could be employed, the integration being automatically performed without any other collecting device. The known source of radiation consisted of a glow lamp which will be referred to as the "comparison lamp," C.L., placed close to the prism (in some cases beneath it, so that both were approximately on the axis of the bench). A standard glow lamp, S.L., was kept continuously burning on the other side of the photometer box, B. A fixed screen, S, with an aperture, served to block off all radiation but that from the prism, P, or comparison lamp, C.L., while a sliding metal screen, S′, actuated by a cord, could be rapidly moved in front of one or the other. In taking the readings the light from the prism was allowed to fall on the bolometer, and the current through the comparison lamp varied until on moving the screen, S′, in front of P or C.L. alternately, no change could be noticed. In this way all disturbances due to external changes of temperature could be eliminated, and the observations were much more rapidly obtained than by waiting for slow deflections.

A glow lamp was used as the standard source of radiation for the following

reasons: (*a*) The total power is easily measured by the P.D. and current, and can be readily regulated; (*b*) the ratio of convection and conduction to radiation is very small, owing to the high temperature of the filament. These advantages render the glow lamp immeasurably superior to low temperature sources such as employed by Thomsen and others. On the other hand the radiation is not uniformly distributed. But this difficulty can be overcome by determining once for all the relation of the intensity in any given direction to the mean spherical emission, and this may conveniently be determined photometrically.

The photometer employed was of a special form devised by the writer for ordinary and heterochromatic measurement. It consists simply of two totally reflecting right-angled prisms, mounted with their edges in contact. When this combination is set up between two lamps, the light from each is reflected forwards, and can be received on a screen placed in contact with the front face of the prism. This screen may be simply of translucent paper, or opal glass, in which case the appearance is identical with that of the Joly paraffin block photometer; or in the form of a discrimination diagram which serves for heterochromatic work. This diagram is made up of letters and reticulations of different sizes, and both on light and dark backgrounds, the letters and designs being absolutely symmetrical. The advantages of this arrangement are, briefly, that it serves either for isochromatic or heterochromatic photometry; it is absolutely symmetrical; it is not affected as are the wedge photometers by a slight inclination to the axis of the photometer bench; it forms a very sensitive cross staff for indicating whether the lamps and the photometer are in line, and whether there is any inclination to the axis; and, lastly, it permits any portion of a spectrum to be brought exactly to the dividing line so that the comparison may be made with a fairly short spectrum on one side.

For the measurement of the energy a pair of thermo-junctions on the lines employed by Professor Féry* was at first made up, but was found insufficiently sensitive. They were therefore replaced by a bolometer, which was made of 50 cm. of 2-mil copper wire wound backwards and forwards on a mica frame, and had a resistance of about 7·5 ohms. Two such bolometers were made and mounted in the same case with the photometer prisms, the centre of the bolometer being carefully adjusted to be over the edge of the prisms so as to be in the part of the spectrum under photometric examination. To protect the bolometers from draughts the two ends of the box and the observing window were covered with quarter-wave mica sheets. The two bolometers were separated by an asbestos screen, and

* "Rayonnement Calorifique et Lumineux," Thèses, Paris, Série A, No. 1111.

were connected to three terminals on the top of the box, from whence three flexible conductors were taken to a Carey-Foster bridge. By having the two bolometers, changes of the air temperature are of less importance, and the whole photometric and radiometric arrangement is reversible. The ratio coils were of 10 ohms each, and a moving coil galvanometer having a resistance of 7·5 ohms and a sensitiveness of 22 mm. per microvolt was employed. The current in each of the bolometer grids was from 0·04 to 0·1 ampère.

In taking the readings the photometer head was first fixed in the middle of the bench, and the spectrum moved until the required colour appeared at the dividing edge between the prisms. The standard lamp was then brought up and balance obtained at a distance, d, from the photometer. Next, the comparison lamp was regulated as above indicated, until the heat balance was obtained, the comparison lamp being at a distance, D, and supplied with power, W, watts. Then, on the assumption that the heat from the comparison lamp was radiated equally in all directions, we have :—

Intensity of radiation at bolometer $\rho = r\mathrm{W}/4\pi\mathrm{D}^2$ watts per square centimetre, where r is the ratio of radiation to total power.

Intensity of illumination of beam $\mathrm{I} = f\mathrm{K}/d^2$, where K is the candle-power of the standard lamp, and f the ratio of the illumination in the direction of the beam to the average illumination.

Hence, the mechanical equivalent of light $\mathrm{M} = \dfrac{4\pi\rho}{\mathrm{I}} = \dfrac{\mathrm{W}r}{\mathrm{K}f}\left(\dfrac{d}{\mathrm{D}}\right)^2$, giving the mechanical equivalent in watts per candle.

A careful determination of the candle power of the comparison lamp in various directions, when kept at a constant P.D., was made by Mr. Jolley, resulting, for the horizontal direction, in a reduction factor of 0·862, agreeing very well with the 0·865 given by Paterson.

For the direction in which the radiation was measured the value of the factor was found to be 0·78.

The amount of heat lost by convection was estimated experimentally by measuring the amount of heat communicated to a suitable calorimeter by the warm air rising from the glow lamp. It was found that the convection loss was not more than 2 or 3 per cent., which could be neglected in view of the accuracy which could be obtained.

The greater number of the observations were made in the yellow-green, which were judged by eye to be in the neighbourhood of $\lambda = 0{\cdot}54\,\mu$ proposed by Guilleaume. Having regard to the fact that the mounting hardly justified accurate determinations of wave-length; that the point $\lambda = 0{\cdot}54\,\mu$ can hardly be said to have been definitely determined as the point of maximum

efficiency; that in the region of maximum efficiency the variation would not probably be great, as was confirmed by test; and lastly, that in order to avoid trouble, owing to the Purkinje effect, it was considered advisable to work at illuminations not exceeding two or three candle-feet, in which case the sensitiveness was not very great, it was considered superfluous to determine the wave-length with greater accuracy. It may be said that the sensitiveness of the arrangement seemed to allow of the definite detection of half a watt at a distance of about 2 metres.

In making determinations on white light, the slit was broadened considerably, and by covering it up from each side successively, it could be adjusted so that light passing one edge of the slit gave a very dark red light on the photometer screen, while that from the other edge gave a deep violet light on it. In this case the result produced by the whole slit was of a pure white light, from which all the invisible radiation was cut off, instead of being only cut off from one end, as in the experiments of Ångström.*

A number of preliminary observations were taken with arc and Nernst lamps as sources of light, and reversing the photometer box, etc. Considerable trouble was, however, found with drifting of the galvanometer, and this was traced to the presence of the observer. The mean result, however, from 24 observations was 0·08 watts per candle power. After this the whole of the apparatus was removed, the photometer bench, sliding screen, etc., being set up in a dark room, through the wall of which an aperture was made for the projection of the spectrum, and a second small aperture for the observation of the photometer. In this way the whole of the observations could be taken without entering the room, and the readings were much more satisfactory.

The results obtained are collected in Table I.

The final result of about 0·12 watt per candle power for the white light from the Nernst filament agrees almost exactly with the value found by Ångström for the Hefner lamps. Thomsen and Tumlirz both used absorption methods, and little value can be attached to their results. Other values can be deduced from investigations on the efficiencies of illuminants, but these values range from 0·0011 to 0·0289 watt per candle found by Wedding, and 0·02 to 0·39 by Rüssner, to 0·19 to 0·49 watt per candle from the results of Merritt.

The lower value of 0·08 watt per candle found in the present tests for

* In Ångström's experiments the glass in the lenses, etc., employed would probably have cut off the major part of the ultra-violet radiation, and the energy in the ultra-violet is generally very small for ordinary sources of light. Hence probably the agreement with our results.

white light from the arc is probably due to the higher temperature of the source. Pending more exact determinations, therefore, it may be assumed that an ideal source of white light should give us about 10 candles per watt, and a monochromatic yellow-green source nearly 17 candles per watt.

Table I.—Observations on the Mechanical Equivalent of Light.

Standard lamp.		Comparison lamp.				Mechanical equivalent, $M = \frac{W}{0{\cdot}78\,K}\left(\frac{d}{D}\right)^2$.
Distance, *d*.	Candle power, K.	Distance, D.	Current, ampères.	P.D., volts.	Watts, W.	
(A) Light approximately monochromatic, yellow-green.						
80·0	24·5	116·7	0·145	31·8	4·61	0·0555
80·0	24·5	166·7	0·13	29·0	3·77	0·0455
70·6	24·5	165·5	0·15	32·6	4·9	0·0468
78·0	20·6	165·5	0·145	31·8	4·48	0·0620
78·0	20·6	165·5	0·16	34·5	5·52	0·0765
78·0	24·5	165·5	0·17	36·2	6·15	0·0715
85·0	24·5	165·5	0·15	32·4	4·85	0·0670
76·3	24·5	165·5	0·155	33·2	5·15	0·0573
7676·3	20·6	165·5	0·145	31·6	4·58	0·0605
76·3	24·5	165·5	0·15	32·2	4·83	0·0536
57·4	24·5	165·5	0·23	45·0	9·9	0·0622
121·0	24·5	165·5	0·095	22·2	2·11	0·0590
					Mean ...	0·0598
(B) White light from wide slit.						
149·0	16·0	206·0	0·115	26·3	3·03	0·127 } Nernst filament
86·0	13·0	263·0	0·225	47·0	16·6	0·1115 } Nernst filament
					Mean ...	0·1193
76·1	16·0	263·5	0·23	47·5	10·9	0·073 } Arc
75·0	16·0	263·5	0·25	50·5	12·6	0·082 } Arc
89·6	24·5	166·5	0·16	34·4	5·5	0·0835 } Arc
89·6	24·5	166·5	0·16	34·4	5·5	0·0835 } Arc
					Mean ...	0·0805

Table II.—Mechanical Equivalent of Light.

Collected Values.

Observer.	Date.	Method.	Source.	Unit.	Mechanical equivalent.			
					Calories per second.		Watts.	
					Per Hefner.	Per C.P.	Per Hefner.	Per C.P.
J. Thomsen	1863	A.	Sperm candle	Sperm candle, 8·2 grammes per hour	0·065	0·0733	0·276	0·3075
	,,	,,	Moderator lamp		0·0585	0·065	0·245	0·272
	,,	,,			0·0615	0·0683	0·257	0·286
	,,	,,	Gas flame		0·063	0·070	0·264	0·293
	,,	,,			0·0553	0·0615	0·232	0·258
O. Tumlirz and Krug	1888	A.	Incandescent platinum wire	Hefner	0·041	0·0455	0·1715	0·19
O. Tumlirz	1889	A.	Hefner lamp	Hefner	0·0455	0·0505	0·191	0·212
K. Ångström	1903	C.	Hefner lamp	Hefner	0·0259	0·0288	0·1085	0·121
Writer and A. C. Jolley	1907	C.	Nernst filament	Candle	0·0256	0·0284	0·107	0·119
	,,	,,	Arc	,,	0·0173	0·0192	0·0725	0·0805
	,,	,,	Monochromatic, yellow-green	,,	0·01285	0·0143	0·0538	0·0598

Method A.—Thermopile and absorptive screens.
Method C.—Direct measurement of energy in spectrum.
In this table the Hefner has been taken as 0·90 C.P. See Paterson, 'Proc. Inst. E. E.,' vol. 38, p. 286, and Fleming, p. 311.